AFRL-SR-AR-TR-09-0285

REPORT DOCUMENTATION PAGE

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
05-06-2009	Final Performance Report	15-09-2006 to 31-05-2009

4. TITLE AND SUBTITLE
NonLinearities and Wave Mixing Properties of Negative Index Materials (Nanotechnology Initiative)

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-06-1-0547

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
FA9550-06-1-0547 - Final

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
USAF, AFRL, AF Office of Scientific Research
875 North Randolph Street, Rm 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
USAF, AFRL, AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release: distribution is unlimited

20090914176

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The primary goal of this project was to develop new ideas in the area of nonlinearities in negative refractive index media, with particular focus on the optical regime as this is a regime that exhibits strong nonlinearities. As metamaterials are composed of sub-wavelength unit cells by their very nature, metamaterials in the optical regime are nanostructures. Thus, the research directly addressed novel nonlinear effects in nanostructured negative index metamaterials. The specific nonlinearities that were studied were the nonlinear susceptibilities, nonlinear wave-mixing, and long wave short wave resonance properties of negative refractive index media. The research in this area revealed that nonlinear metamaterials could be used for distortion/nonlinearity compensation, perfectly phase matched wavelength conversion and terahertz generation from optical pulses

15. SUBJECT TERMS
Negative refractive index media
Metamaterials

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
				3	Dr. Aref Chowdhury
					19b. TELEPHONE NUMBER *(Include area code)* (908) 582-2173

Final Performance Report 2006-2009

Grant Title: Nonlinearities and Wave Mixing Properties of Negative Index Materials (Nanotechnology Initiative)
Grant Award No.: FA9550-06-1-0547
Principal Investigator: Aref Chowdhury (Bell Labs, Alcatel-Lucent)
Reporting Period: September 15, 2006 to May 31, 2009

Project Accomplishments:

The primary goal of this project was to develop new ideas in the area of nonlinearities in negative refractive index media, with particular focus on the optical regime as this is a regime that exhibits strong nonlinearities. As metamaterials are composed of subwavelength unit cells by their very nature, metamaterials in the optical regime are nanostructures. Thus, the research directly addressed novel nonlinear effects in nano-structured negative index metamaterials. The specific nonlinearities that were studied were the nonlinear susceptibilities, nonlinear wave-mixing and long wave short wave resonance properties of negative refractive index media. The research in this area revealed that nonlinear metamaterials could be used for distortion/nonlinearity compensation, perfectly phase matched wavelength conversion and terahertz generation from optical pulses.

We theoretically explored the effective second-order and third-order nonlinear susceptibilities as well as the three-wave mixing (nondegenerate) and four-wave mixing properties of negative refractive index materials. An important result that emerged about the nonlinear susceptibilities for both centrosymmetric and noncentrosymmetric metamaterials is that their signs may be positive or negative depending on the frequency of interest relative to the resonant frequencies of the media. A negative refractive index medium/metamaterial with a negative third-order nonlinear susceptibility may be used to compensate nonlinear effects produced by another medium that has a positive third-order nonlinear susceptibility; thus, important applications may be distortion compensation in surface to air communication, and nonlinearity compensation in optical fiber communication systems. Our comprehensive analysis of nonlinear wave-mixing also yielded some very interesting results. We found that perfect phase matching is possible in a variety of collinear three- and four-wave mixing configurations if at least one of the interacting waves is in the negative index regime. Our study on nonlinear wave mixing in negative index media opens up the possibility for a new class of wavelength converters.

We discovered that the nonlinear phenomena of long wave short wave (LWSW) resonance can be realized in negative refractive index media. Long wave short wave resonance occurs when the group velocity of a short wave (high frequency wave) is equal to the phase velocity of a long wave (low frequency wave). Owing to the dispersion relation of negative index media, it is possible to satisfy the LWSW resonance condition when the short wave lies on the negative branch (thus exhibiting negative refractive index) of the dispersion curve. We found that the coupled equations that govern the resonance condition have a pondermotive force term, which is the spatial variation of the optical power density that essentially drives the system. However, our work introduced the concept of using a second-order nonlinearity for efficient resonant coupling, which is different from past work done in the area of slow light where the pondermotive force alone was the local nonlinearity. The source of the second-order nonlinearity in a metamaterial may be from the background dielectric or from the inherent response of the negative index medium. We also showed that a number of interesting solutions exist depending on the effective material parameters of the medium. The solutions include solitary waves, paired solitons and periodic wavetrains. The major application of such a resonance is the generation of terahertz waves from an input optical wave. We consider this to be a breakthrough application of metamaterials as terahertz radiation has a variety of important applications including security, imaging, sensing and spectroscopy.

In conclusion, the research in the area of nonlinearities of negative refractive index media has revealed novel phenomena in as well as important applications for metamaterials. Future research in this area may provide further breakthrough ideas and applications for negative refractive index media.

Publications:
1. A. Chowdhury and J. A. Tataronis, "Long Wave–Short Wave Resonance in Nonlinear Negative Refractive Index Media," *Physical Review Letters*, Vol. **100**, 153905, April 2008.
2. A. Chowdhury and J. A. Tataronis, "Nonlinear Wave Mixing and Susceptibility Properties of Negative Refractive Index Materials," *Physical Review E*, Vol. **75**, 016603, January 2007.

Conferences:
1. A. Chowdhury, "Nonlinearities in Negative Refractive Index Media," *Nonlinear Optics: Materials, Fundamentals and Applications*, Kona, HI (2007) (**Invited**).
2. A. Chowdhury, M. Saboktakin, and J. A. Tataronis, "Four-Wave Mixing in Negative Refractive Index Media," *Photonic Metamaterials: From Random to Periodic*, Jackson Hole, WY (2007).

Patents:
1. A. Chowdhury and P. M. Platzman, "Chirped Metamaterials," U. S. Patent Pending.
2. A. Chowdhury, "Cloaking Device Detection System," U. S. Patent Pending.
3. A. Chowdhury and J. A. Tataronis, "Negative Refractive Index Device for Generating Terahertz or Microwave Radiation and Method of Operation Thereof," U. S. Patent Pending.
4. G. Blumberg and A. Chowdhury, "Conductive Polymer Metamaterials," U. S. Patent Pending.
5. A. Chowdhury, "Polarization-Diverse Negative Refractive Index Apparatus and Methods," U. S. Patent Pending.
6. A. Chowdhury and J. A. Tataronis, "Nonlinear Optical Devices Based on Metamaterials," U. S. Patent Pending.

Changes in Research Objectives: None

Change in AFOSR Program Manager: None

Extensions Granted or Milestones Slipped: None